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THE NATURE AND LOCALIZATION OF CHROMOSPHERIC FLARES

by Yu. M. Slonim

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THE NATURE AND LOCALIZATION OF CHROMOSPHERIC FLARES

Yu. M. Slonim

ABSTRACT

The relationship of flares to solar prominences has been discussed. Three types of flares are considered. Type A is shown to have plasma with sharp, short pulse jets, Type B a strong, contracted radiation burst, and Type C a long-duration pulsating character. The first two appear strictly in the chromosphere, whereas Type C has a coronal origin. In order to compare these various flare types objectively, the flare intensity was replaced by the line width characteristic H_α. It is shown that Type C flares are generated principally in the growth phase of sunspot groups, whereas Types A and B are found in the decaying phase. It is concluded that these facts show the differences between the fast-growing flares of Types A and B, and the pulsating flares of Type C. The analysis is extended to connect Type C flares with loop prominences. Various reasons are given for the hypothesis, emphasizing the similarity between pulsating emission center for Type C flares and the nature of nodal and jet radiation of prominences. Two significant observations are cited: the first on April 5, 1960 in group No. 144, and the second on December 18, 1956, in the case cited by H. Zirin (Ap. J., 129, 414, 1959). This latter observation supports the hypothesis that Type C flares are generated in the solar corona, and form spatial multistage structures.

The process of development of the chromospheric flares does not fit within the characteristics of the general scheme. Aside from the widely observed type of flares which is characterized by a rapid instantaneous flareup and a distinct brightness maximum, followed by relatively slow decaying of the emission center, other flares are observed which do not have these characteristics, but which undergo prolonged, repeated brightness pulsations.

We have studied the relationship between flares and solar prominences and have determined that these processes follow each other in active regions as well as beyond these regions. Relying on the apparent

close relationship between these two types of solar activities, we have classified these flares into three types (Refs. 1, 2), on the basis of their relationship to the prominences. The flares are followed by the eruptions of chromospheric matter (partially returnable), and in such cases when the eruptions of plasma are so intense, they have a characteristically brief pulsation (Type A).

Another type of flare which encountered somewhat less frequently is followed by a slow outflow of chromospheric matter with a constant speed of about 10 km/sec, which leads to the formation of prominences closely resembling loops (Figure 1, B1-B4). In this instance the flare is characterized by a powerful, prolonged radiation burst (Type B). The third type of flare is associated with the influx of loops, flows and streams /68
of the coronal prominences. In this type of influx, the flare is characterized by a prolonged, pulsating nature (Type C). This type of flare is in accord with the delayed and intermittent development of similar prominences (Class Ps modified by de Jager (Ref. 3), (according to the Pettit scheme). Brightness pulsations of the emission center can break down into a series of more or less isolated maxima or flow out as a continuous uninterrupted fluctuation chain without separate flares. The characteristics of development of each of the three types of flares are easily observed in Figure 2, in which the data on their brightness I(t) is given. The data given in Figure 2 are taken from the original films of the Tashkent Astronomical Observatory which were obtained on the microphotometer (MF-2).

The fast-growing flares of Types A and B, which are followed by the eruption of chromospheric matter, and the lagging, pulsating flares of Type C, which are related to the outflow of the coronal matter, are, in our opinion, basically different from each other in their characteristics. The flares of the first two types are inherently chromospheric, whereas flares of Type C are of coronal origin. The basic differences in the nature of these two processes can be seen not only in the curves showing their brightness, but also in a series of additional characteristics. Thus, researchers at Kiev recently pointed out that there are two types of flares, one having a distinct relationship between the area of the emission center and its brightness in maximum, and the other type having no correlation between these two characteristics (Ref. 4) which can be observed.

Using the cumulative data on flares published in The Quarterly Bulletin on Solar Activity (Ref. 5), we have established that Type C flares do not conform to these characteristics. The division of flares into two groups, pulsating (Type C) and fast-growing (Types A and B), was done on the basis of such characteristics as the general duration of the process, the rate of increase of brightness to its maximum, the presence of repetitive fluctuations, small amplitude of brightness, and so on. In this study, only data was used from stations which filmed the flares using the

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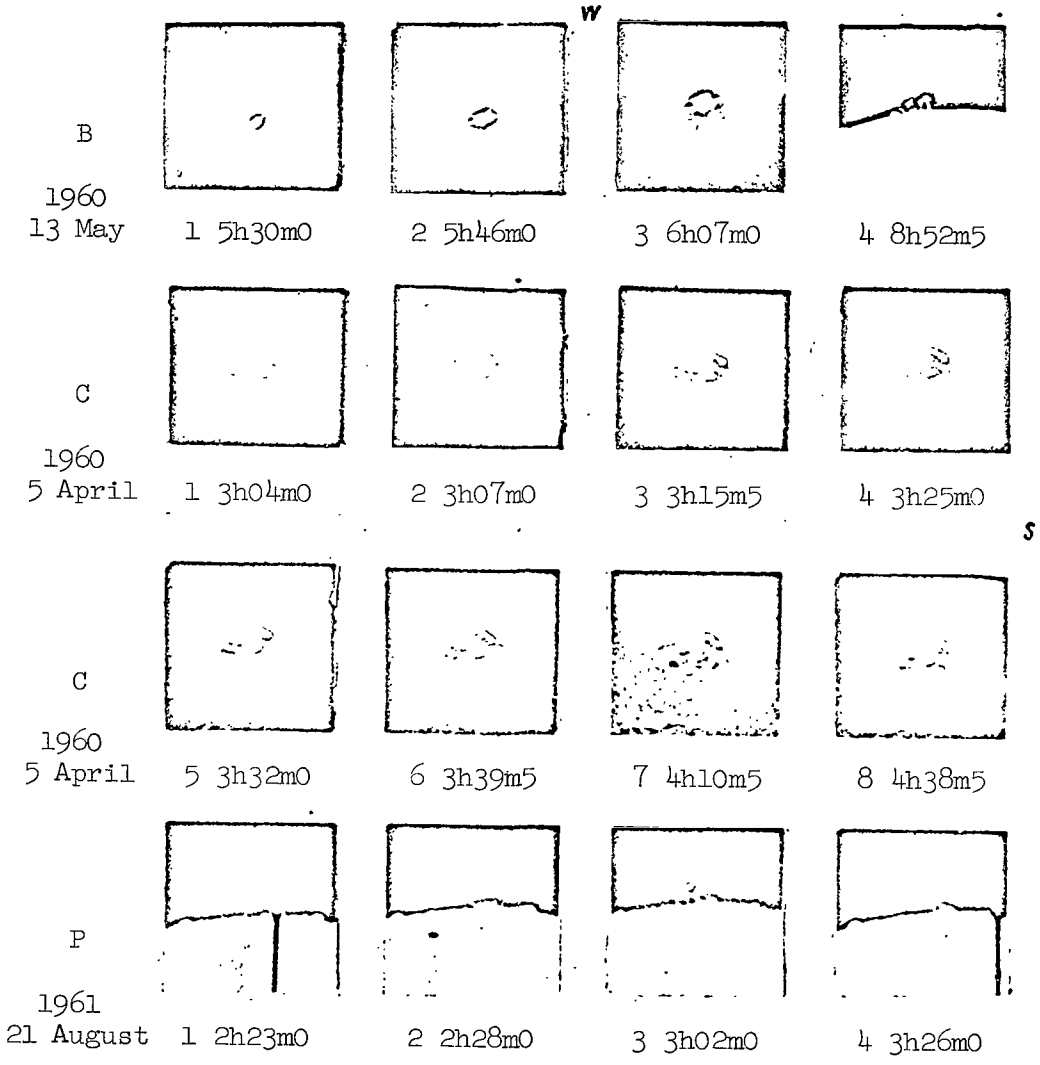

Figure 1

interference polarizing filters, thus ensuring a reliable area definition. Considering the variety of the photometric systems of the individual stations, we have substituted for the intensity of the flare, the width of line H_α, which gave us a more objective characteristic. Altogether we have studied 319 processes. The mean values of the width of H_α inside a given area interval are shown in Figure 3; the crosses

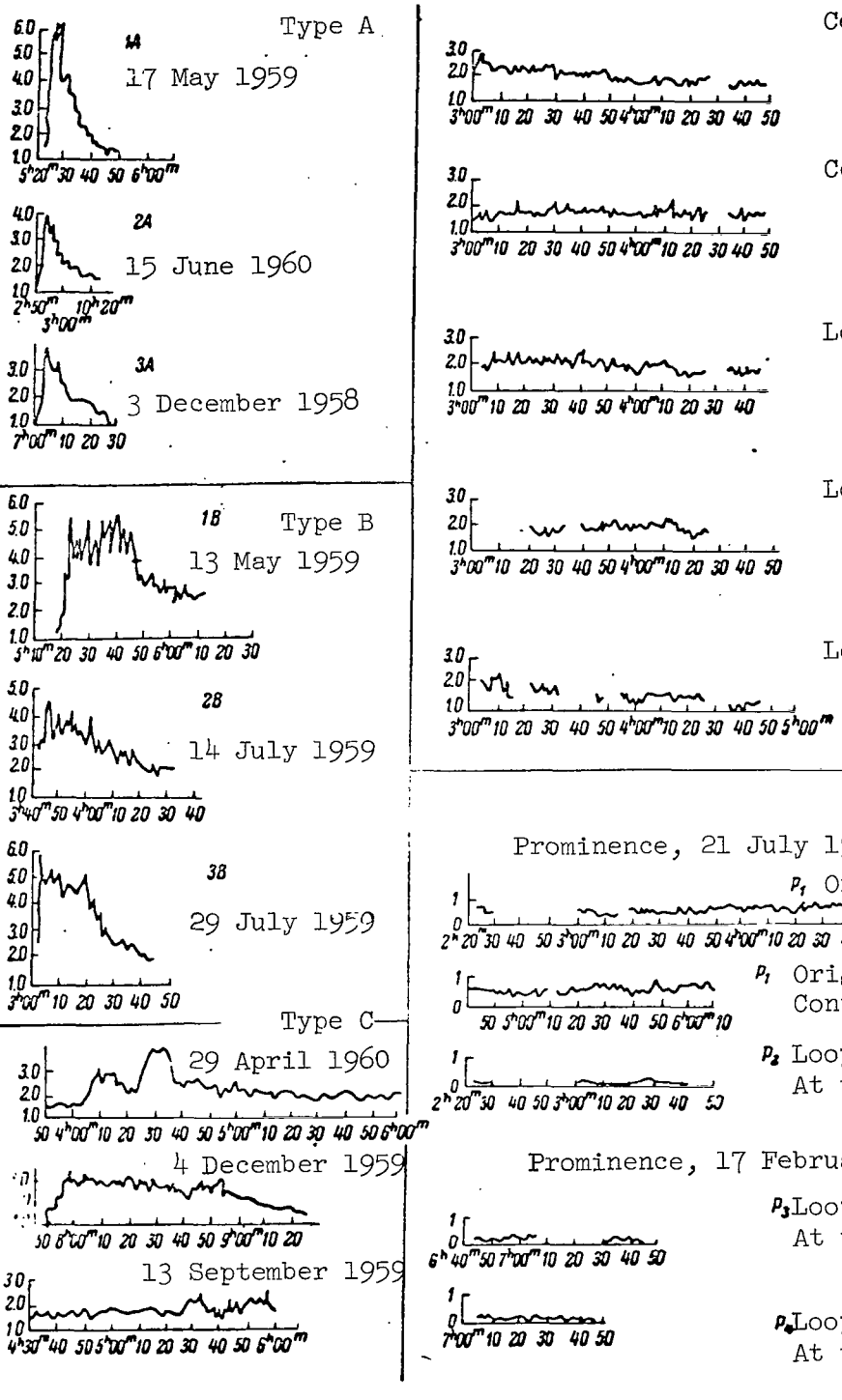
Type A
1A
17 May 1959
2A
15 June 1960
3A
3 December 1958
Type B
1B
13 May 1959
2B
14 July 1959
3B
29 July 1959
Type C
1C
29 April 1960
2C
4 December 1959
3C
13 September 1959
Center a
Center b
Loop c
Loop d
Loop e
Prominence, 21 July 1961
P_1 Origin
P_1 Origin
Continuation
P_2 Loop
At the top
Prominence, 17 February 1960
P_3 Loop a
At the top
P_4 Loop b
At the top

Figure 2

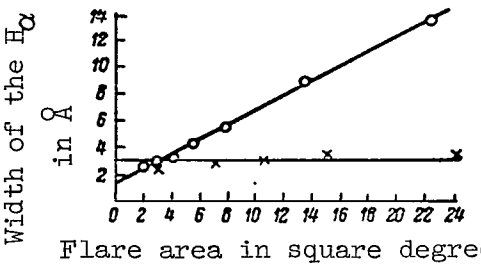

Figure 3

represent Type C flares, and the circles represent Types A and B flares. In the fast-growing Types A and B flares, the width of H_α, and consequently the brightness, is unquestionably related to the area, but the pulsating Type C flares have no such dependence. They can all spread out to considerable areas within the flocculent field, but are always characterized by a small width of H_α (of the order 3 Å), that is, by the absence of protracted wings. These are weak flares; their brightness is seldom higher than the intensity of the continuous spectrum near the H_α line. /70

We observed the distribution of Type C flares and of Types A and B flares during the whole duration of evolution of a group of sunspots. The study which is based on the material (Ref. 5) (characteristics of the flares), and the observations of the Tashkent Astronomical Observatory (characteristics of the groups), has shown that Type C originates primarily in the growth phase of the group, and that Types A and B originate in its decaying phase. This conclusion is illustrated with the data in Figure 4, in which the solid black curve represents the growth of the area of a group. Its ascending and its descending branches are symmetrical, since the argument T is expressed in portions of the phase of growth and decay. The thin solid curve represents the frequency of Type C flares, and the broken curve represents the frequency of Types A and B flares. The predominance of Type C flares during the period of growth of the area of a group, and consequently of the increase of the intensity of the magnetic field, can be distinctly observed in this graph.

The relationship between Type C flares, with the growth processes of the area of a group and the intensity of the field of the region, becomes even more apparent when the prolonged brightness pulsations of the flocculent field, characteristic of this type of flare, go on for hours and sometimes even days. Examples of such practically continuous pulsations are given in Table 1; however, at present they cannot be differentiated into separate flares. Here the data on flares are based on materials

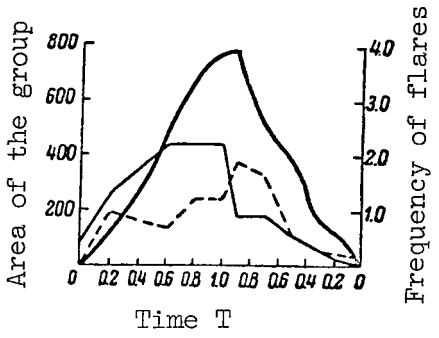

Figure 4

(stated in Ref. 5) and data on the area of the sunspot group from the bulletin "Solar Data." In a predominant number of cases studied (in 13 out of 17, according to Table 1, or 76 percent), such uninterrupted chains of flares are connected with the formation or growth of a group, and frequently many groups, which develop with extreme intensity.

All these facts indicate the physical differences in the characteristics of the fast-growing layers of Types A and B, and the pulsating flares of Type C, which in our view are of coronal origin. The interrelationship between the flares with coronal prominences has been presented for discussion on several occasions during the past few years.

In 1959 the author (Ref. 1) demonstrated that the flares seem to have a tendency to be localized in the bright prominences of the chromosphere, where the streams and loops of the near sunspot prominences (i.e., Class Ps, de Jager scheme) are focused. The connection between the flares with loop prominences and their tendency to be localized at the base of the loops was noted independently by Roberts (Ref. 6). Recently Menzel came to the conclusion that the brightest flares observed /71 through the integrated light are identical to the loop prominences (Ref. 7). Finally, the most natural proof of the relationship of flares to the near sunspot coronal prominences can be concluded on the basis of the similarity of their spectra (Refs. 8-11). It is not absolutely clear, however, if this similarity is explained by the fact that these phenomena represent different branches or phases of the same process, or on the other hand, that some flares are identical to the coronal prominences.

We are inclined to think that Type C flares originate in the coronal space and gradually disperse into lower layers; consequently, they represent processes which at first encompass the corona and later the chromosphere. It should be noted that the increase in the intensity of the magnetic field which follows such flares, according to the conclusions of V. A. Krat and V. M. Sobolev (as stated in Ref. 12), promote a condensation of the coronal matter over the group, and its subsequent cooling

Table 1

Year	No. of region	Coordinates of region			Characteristics of the chain of flares						Phenomena in the photosphere
					Begin		End		No. of flares	Total duration of flares	
		φ	λ	Ts. M.	Date	Hours	Date	Hours			
1957	1	+16°	291°	30^d 9 Sep	23 Sep	2313	24 Sep	0950	11	>0530 hr	Growth of the group: 24 Sep area 590; 25 Sep - 1310 m.d.p.
1958	2	+44	208	9 9 Jun	5 Jun	2128	6 Jun	1636	18	>0620	Violent development of the group: 4 Jun area 31; 6 Jun - 755 m.d.p.
	3	+15	102	17 9 Jun	18 Jun	2348	19 Jun	1629	9	>0920	Between 19 Jun and 20 Jun violent growth of the leader in the group; with the concentration of flares near it.
	4	+27	203	7 5 Jul	7 Jul	0026	7 Jul	1705	6	>0340	Developing group: 4 Jul area 145, 7 Jul - 802 m.d.p.
	5	-23	202	7 6 Jul	9 Jul	0848	10 Jul	1705	17	>1530	Formation of a large sunspot; 9 Jul group area 854, 10 Jul - 1520 m.d.p.
	6	-20	155	7 3 Aug	11 Aug	0415	11 Aug	0816	6	>0115	Formation of the leader of the group: 10 Aug area 134, 11 Aug - 345 m.d.p.
	7	-11	131	9 2 Aug	13 Aug	0036	13 Aug	1040	6	>0240	Development of the group: 12 Aug area 351, 13 Aug - 478 m.d.p.

Table 1 (continued)

Year	No. of region	Coordinates of region			Characteristics of the chain of flares						Phenomena in the photosphere
					Begin		End		No. of flares	Total duration of flares	
		φ	λ	Ts. M.	Date	Hours	Date	Hours			
	8	-14°	87°	12 5 Aug	13 Aug	1055	14 Aug	1225	23	>1800 hr	Growth of the sunspot: 13 Aug area 1110, 15 Aug - 1395 m.d.p.
1958	9	-31	346	16 4 Sep	13 Sep	0318	13 Sep	1217	5	>0730	Constant area
	10	+ 3	166	30 0 Sep	3 Oct	0552	3 Oct	2011	8	>0410	Development of the group: 2 Oct area 178, 4 Oct - 351 m.d.p.
	11	- 4	258	20 3 Oct	13 Oct	0904	15 Oct	2112	27	>2530	Development of the group: 14 Oct area 640, 16 Oct - 1320 m.d.p.
	12	+22	216	17 1 Dec	15 Dec	0052	16 Dec	1503	18	>0620	Constant area
1959	13	+17	64	21 3 Feb	19 Feb	0745	19 Feb	1532	6	>0430	Constant area
	14	+26	286	31 2 Mar	26 Mar	0311	26 Mar	2147	10	>0700	Rapidly developing group: 26 Mar area 836; 30 Mar - 1500 m.d.p.
	15	+17	329	17 6 Jun	15 Jun	0110	15 Jun	1708	10	>1050	Constant area
1960	16	+12	130	31 5 Mar	4 Apr	0010	6 Apr	1653	26-27	>1350	Between 5 Apr and 6 Apr the development of the area of the group.
	17	+20	70	25 8 Jun	30 Jun	0220	1 Jul	2022	16	>0930	Between 29 Jun and 1 Aug the growth of the area from 367 to 510 m.d.p.

and lowering into the sunspot. There is convincing evidence which leads us to suppose that some of the flare centers of Type C are located at a much higher level than the chromospheric flares of Type A. Partial localization of Type C flares in the coronal space can be based in a series of proofs:

1. The pulsating character of brightness of many emission centers of Type C flares is very similar to the characteristics of nodal and jet radiation of prominences which form in the corona above the sunspots (compare the curves 2C - 3C, P_1 - P_4 in Figure 2). Therefore, it is natural to suppose that the nodal and jet radiation of prominences of the C flares are explained by their higher localization and coronal origin.

2. Interaction with the coronal matter can be explained by using the data (Ref. 5) obtained in the observation of the helium line in the emission. Altogether, 49 flares were observed. According to our calculations, 34 of them, that is 70 percent, belonged either to Type C (29 flares) or were distributed far into the corona, and were of the Type B (5 powerful flares).

3. Using the same interaction with the coronal plasma, it can be explained that the appearance of Balmer's continuum in the emission indicates the presence of the recombination processes, and was observed primarily in Type C flares (in six cases out of eight, according to the same calculations based on materials (Ref. 5)).

4. On the basis of the studies in Refs. 13, 14, the regenerating flares (Type C) are frequently located on the neutral line of the longitudinal BMR field, in other words, in the upper layers of the corona formed by force lines, which means that these flares are localized in the coronal space above the group. /74

5. It has been stated on several occasions (Refs. 15, 16) that weak flares have a tendency to distribute themselves along the trajectory of the active BMR plasma. This fact also indicates that they originate above the chromospheric level and later descend into it.

6. Finally, as was shown by the statistical study done by Warwick (Ref. 17), the greatest height above the chromosphere is reached by the weak flares, that is, basically by Type C flares.

All of these data are in accord with the hypothesis of the coronal origin of Type C flares, and indicate the relatively high localization of some of the loops and their relationship to the formations of coronal prominences above the sunspots.

Of great significance, in the sense of the nature of the type under study, is the flare observed on April 5, 1960, in the group number 144 (enumeration according to the bulletin, "Solar Data"); $\varphi = 12^{\circ}$, $\lambda = 130^{\circ}$, Ts. M. = $31^{d}.5$ Sh). After examining the curves showing the brightness of its centers, the absence of extended wings (with $H_{\alpha} \approx 2$ Å), and the uninterrupted pulsation chain (see Number 16, Table 1), it is concluded that the flare on April 5 should be viewed as a classical representative of Type C flares. The characteristic feature of this type of flare was the fact that at the photosphere level, the process was followed by the increase in the area of the group from 1,275 m.d.p. April 5th to 1,570 m.d.p. 6 April (actually the growth of the area was probably much greater, since on April 6 the group has partially moved behind the western edge of the disk).

The flare was observed at the Tashkent Astronomical Observatory from 0300 to 0447 u.t. through the chromospheric telescope (Z. B. Korobovoy), and from 0300 to 0600 u.t. through the spectrohelioscope (K. V. Litvinovich). Immediately after these observations, the flare was observed at the Central Astronomical Observatory, AN SSSR, through the diffractional spectrograph of the horizontal solar telescope, where in the interval from 0605 to 0640 u.t., a series of spectrograms was obtained by V. A. Krat and V. M. Sobolev.

On the basis of the exhaustive analysis of these spectrograms, V. A. Krat and V. M. Sobolev (Ref. 12) found that the flare was followed by a descending movement of helium ($\sqrt{}$ = 10 km/sec), and came to the conclusion that it originated as a result of the cooling off and compression of the corona plasma as it descended towards the sunspot. Further, they have shown that the increase in compression, which was caused by the progressive condensation of gas, caused a counter movement in the much lower and cooler regions of the flare, and was observed in the H and K calcium lines as an ascent of the gas ($\sqrt{}$ = 5 km/sec). Such counterreaction represents, in our opinion, one of the cases of the continuous intermixing of coronal /75 and chromospheric matter in the active regions (Refs. 1, 2).

Films obtained at the Tashkent Astonomical Observatory permit us to see the development of this flare in H_{α}, and to determine its characteristics. This flare consisted (as was shown by films C1 - C8, Figure 1) of stable centers a and b and less stable loops c, d and e, which were connected with a and b by thin leg-like lines (the markings are shown in film C7). These loops were displaced from the sunspot to the edge of the disk with a tangent velocity of about 5 km/sec and the picture of their movement given in Figure 5 is completely in accord with the ascent of matter discovered by V. A. Krat and V. M. Sobolev in H and K. However, in connection with these secondary ascending motions of loops c, d and e, the line shifter indicates the presence of stable descending gas currents

in hydrogen. They are observed in the form of active filaments at the western boundary of the group leader. The filaments change their form but retain their radiation velocities ($\sqrt{}_{avg}$ = 57 km/sec) for a period of

over three hours during the observation. Considering the stable character of the process, we are inclined to classify it as an influx of coronal streams, i.e., as a continuation of such descending streams, which were observed at a much higher level with the aid of helium. On the basis of the observations which were conducted during the same day from 0650 to 1108 hours u.t. by N. M. Fol'dberg-Rogozinskaya (Ref. 11) in the neutral helium line, $\lambda\lambda$ 4,471, 4,713, 5,876; ionized helium, λ 4,686; and, a green coronal line, λ 5,303, the process of condensation and cooling of the coronal matter was just as prolonged and repetitive in nature as the brightness pulsations in H_α (see Table 1), and the centers of con-

densation, i.e., the reservoirs from which the gas moved into the chromosphere, were located high in the coronal space.

A similar series of events were observed on December 18, 1956, and studied by Zirin (Ref. 10), in which the flares along the edge of the disk were followed by the condensation of the clouds of the coronal matter, and the formation of the loop prominence which corresponded to the flare in its brightness. In this case the flares also belonged to the uninterrupted pulsation chain and the group in which they originated (No. 467 according to the bulletin, "Solar Data"), was characterized by the rapid growth of area, i.e., by the intensity of the magnetic field.

The cited examples confirm our conclusion that Type C flares originate in the corona and represent spatial multistage structures. An observation made on April 5, 1960, showed that in addition to the flare centers observed in the helium lines, there were two other levels in the hydrogen line. These were the stable centers a and b and the loops c, d and e which emanated from them. The stable centers a and b, which were located directly above the main nuclei of the group, correspond to the lower stage of the flare, the chromospheric prominences. Joined with them by thin leg-like connections, the loops c, d and e can be easily identified as corresponding to the characteristic structures of many near sunspot prominences namely with those poles-condensations which are located along the edge above the chromospheric prominences (compare C1 - C8 and P1 - P4 in Figure 1). In this case the middle stage of the flare observed on April 5 represents a typical prominence of the Class Ps_2 (Ref. 3), /76

which was observed in the emission on the disk. This conclusion is supported by the luminescence of the centers a, b, c, d and e. The curves of their brightness (a-e in Figure 2) are much closer in nature to the curves of the brightness of the prominence of the Class Ps (see P_1-P_4 in

Figure 2), rather than with the curves of the flares Type A and B (1A - 3A and 1B - 3B in Figure 2).

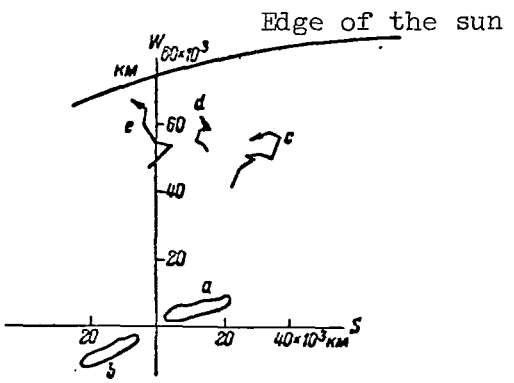

Figure 5

Type C flares should be viewed as complicated spatial processes arising under the conditions of growing magnetic fields and representing one of the phases in the exchange of matter between the corona and the chromosphere. On the basis of their origin, they should be classified as coronal flares, to distinguish them from the inherently chromospheric flares of Types A and B.

In conclusion, the author expresses his sincere gratitude to Z. B. Korobova, who prepared the photometric measurements of the flare which occurred on April 5, 1960, and the prominences on February 17, 1960, and July 21, 1961, and who also measured the tangental line representing the velocities of the moving loops c, d and e.

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